

# Exploitation of elevation angle control for a 2-D HF skywave radar

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**Abstract**— ONERA, sponsored by the French Ministry of defence (Aeronautics program department SPAé), has conducted the realization and experimentations of the skywave HF radar, called NOSTRADAMUS.

This is a new concept of Over The Horizon radar constituted of a monostatic surface array on a three arms star. This choice of structure allows an azimuthal coverage of 360 degrees and elevation beam forming capability.

This paper presents the NOSTRADAMUS system and describes the real time frequency management system of the radar by using the elevation focalization. We present new soundings techniques which have been developed and implemented in the management of the system such as the radar is completely autonomous.

## I. INTRODUCTION

Skywave HF radar principle needs to have a good knowledge of the ionosphere. The operability of those systems needs the implementation of a real-time frequency management system (FMS), based on prediction programs and sounding measurements of the medium.

The ionospheric predictions algorithms generally give median values which can be re-actualized by measurements in situ. Different kinds of soundings of the ionosphere are performed with oblique/vertical sounders at mid-path and backscatter sounders. The output data issued from these external items are used in real-time for the modelling of the medium and the computing of optimum frequencies for the mission of the main radar.

2D radar like NOSTRADAMUS system, allows focalizing the beam in elevation and measuring the angle of arrival of each ray propagated through the ionosphere. New sounding techniques exploiting these capabilities have been developed such as the radar is completely autonomous with no need of external sounding means.

NOSTRADAMUS radar is an original concept of HF skywave system. It is a monostatic and surface array as a 3 arms star. This choice of structure allows 360 degrees coverage in azimuth and the control of the beam in elevation. This monostatic configuration limits the problems of propagation. There is only one reflection point to consider.

During the radar operating mode, the ionosphere is continuously probed. The FMS determines the optimum operating frequency in real time and elaborates the coordinate registration by re-actualizing the 3D ionospheric model and the modelling of the propagation.

## II. NOSTRADAMUS PROJECT

### A. NOSTRADAMUS System

#### 1) 2-D antennas array

NOSTRADAMUS array is a surface array structured as a star with 3 arms spaced of 120 degrees (cf. figure n°1). Each arm is near 400 meters long. The antennas are randomly distributed on 80 meters width along the arms. The elementary antenna is a biconical one (7 meters high by 6 meters width) with an omnidirectional pattern in azimuth. The array association as a star allows all azimuth coverage and the control of the beam in elevation.

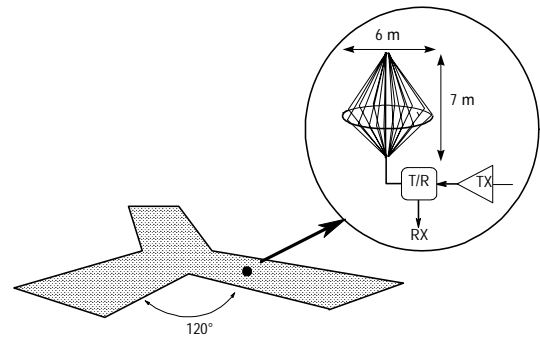


Fig. 1. NOSTRADAMUS array

One part of antennas is used for transmitting and the whole array for receiving (cf. fig. n°2). It is also possible to form simultaneously narrow receiving beams in the two dimensions azimuth and elevation in the footprint of the wide transmitting beam.

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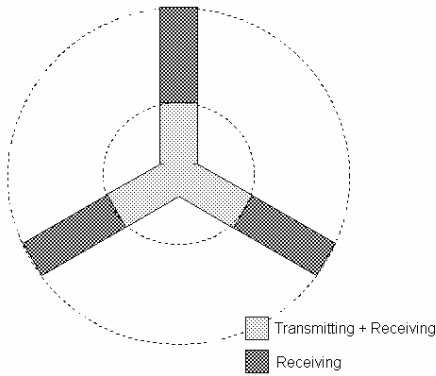


Fig. 2. Diagram of NOSTRADAMUS array

### 2) Transmitting system

One hundred transmitters associated to each transmitting antenna, constitute the transmitting system of NOSTRADAMUS radar. They are installed in underground technical tunnels under each arm of the array.

### 3) Receiving system

The whole array is used for receiving. Antennas are grouped in sub-arrays in order to reduce the quantity of data in the computer. Each signal issued from each sub-array receiver is digitalized and the simultaneous receiving beams are formed by the computing.

## B. NOSTRADAMUS computing system

The management of the radar and the signal processing are realized with a computing system consisting of a 16 bits data acquisition system and a real time computer associated to a network of work-stations. Many work-stations are equipped with their own data acquisition system for the test procedures and the calibration of the radar.

### 1) Beam forming

The surface array allows forming beams in the two dimensions azimuth and elevation. Simultaneous receiving beams are formed in the footprint covered with the transmitting beam. This receiving beam forming is realized in parallel by the computer.

### 2) Radar processing

Signal processing consists in a range - Doppler analysis of the backscattered echoes in each receiving channel. All the channels are treated simultaneously in parallel with NOSTRADAMUS computer.

The outputs of the signal processing are 3D images [amplitude - Doppler - range] obtained for each beam. They contain the radar detection informations characterized by:

- the group range, determined by correlation with the replica of the transmitted signal,
- the Doppler frequency obtained by Fourier spectral analysis.

### 3) Data processing

The building and the visualization of the detected targets

tracks are realized in the data processing by the following process:

- detection of the presence of targets from the data issued from signal processing,
- extraction of the radar plots associated to detected targets,
- coordinate registration (radar parameters are re-computing from the group range to ground range association)
- visualization of the tracks of the targets on radar screens.

## III. FREQUENCY MANAGEMENT SYSTEM (FMS) FOR NOSTRADAMUS RADAR

An Over-The-Horizon radar needs to have a good knowledge of the propagation through the medium, compared to HF communications by ionospheric links. The operating frequency must be chosen in function of the ionospheric conditions determined in real-time and in function of the kinds of missions of detection for the radar (aircraft, ships or other ...).

Aircraft targets are discriminated from the ground echoes by the Doppler. For this mission, the radar must be optimized to illuminate the target with the maximum energy.

Ships echoes have Doppler shifts closed to the sea clutter and sometimes between the Bragg lines for low speed boats. So we need to have a good quality propagation by selecting the adapted frequency in terms of single mode of propagation by optimizing the elevation angle and reducing the ionospheric contamination.

The frequency management of the radar gives optimum operating frequencies to cover the surveillance area from the modelling of ionospheric propagation and from different kinds of sounding performed with the radar. Sounding processes are overlapped in the radar waveform. The characteristic parameters of the ionospheric modelling are determined and used for the computing of the coordinate registration for the targets tracking.

### A. Backscatter soundings

Backscatter soundings consist to analyse the echoes backscattered by the ground. These sounding processes can be differentiated by their operating modes. The different kinds of backscatter soundings implemented in NOSTRADAMUS are:

- Frequency sweep sounding,
- Scanning of the beam in elevation.

#### 1) Backscatter sounding by frequency sweeping

This sounding technique gives directly an overview of the conditions of propagation in function of azimuth, range and frequency. This consists to transmit with the radar, bursts of recurrences for frequencies between 6 MHz to 28 MHz. The signal backscattered by the ground, is sampled just after the receiving, and analysed to determine the energy returning from different ranges. This process is done in each receiving beams (azimuth and elevation). The results are combined to

give two 3D images called ionograms, which represent respectively amplitude and elevation versus range and frequency.

Examples of ionograms obtained with NOSTRADAMUS are shown on figures below (raw data).

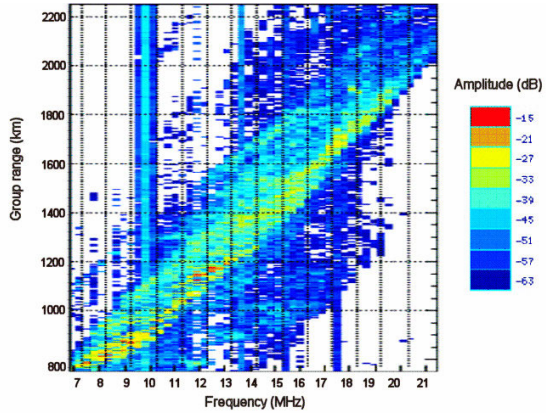


Fig. 3. Amplitude backscatter ionogram

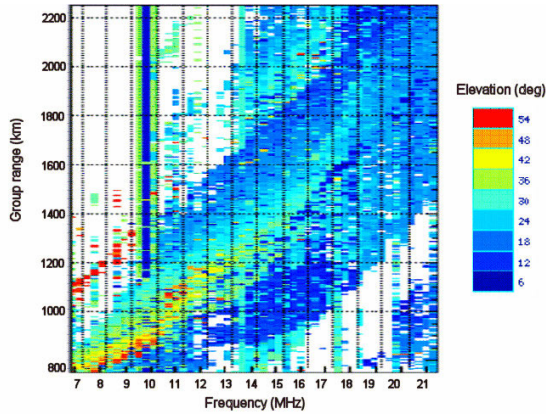


Fig. 4. Elevation Backscatter ionogram

The ionograms are cleaned and filtered by signal and image processing techniques. The measurement of the elevation allows converting the group range in ground range with the global hypothesis of absence of horizontal gradient.

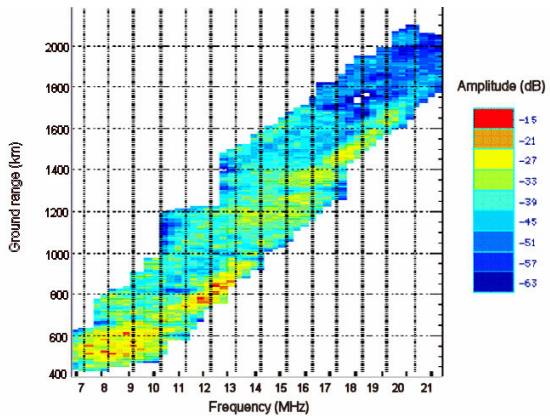


Fig. 5. Amplitude backscatter ionogram in ground range

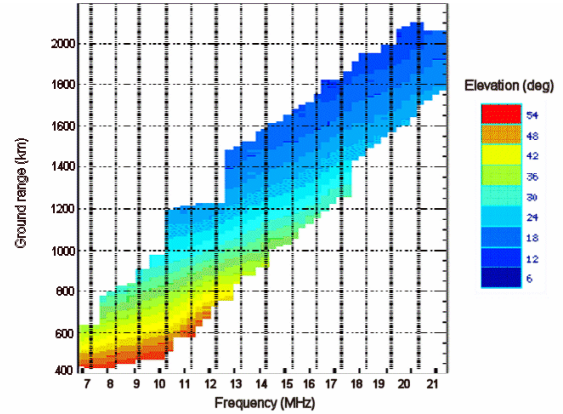


Fig. 6. Elevation Backscatter ionogram in ground range

Criteria have been defined to determine the most energetic frequencies and the optimum elevations in terms of signal to noise ratio for radar detection. The figures below represent the results of this analysis, which will be used in the frequency management for the desired coverage of the radar.

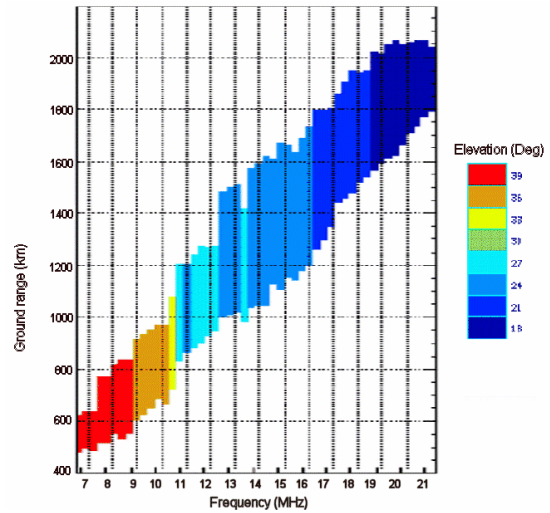


Fig. 7. Backscatter ionogram - Choice of optimum elevation

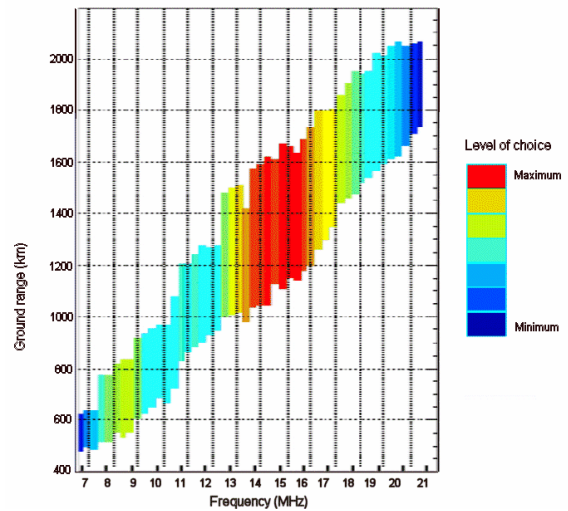


Fig. 8. - Backscatter ionogram - Choice of optimum frequencies

In this example, the best conditions for optimal detection are obtained with a frequency between 14 MHz to 16 MHz with an elevation angle of 24 degrees.

## 2) Backscatter sounding by scanning in elevation

The principle consists to scan the beam of the radar in elevation in a fixed azimuth at one operating frequency. The delay of the clutter echo is measured for each angle of elevation. A 3D image [amplitude – elevation – group range] is generated.

An example of such an ionogram is presented below. High angles correspond to short distances.

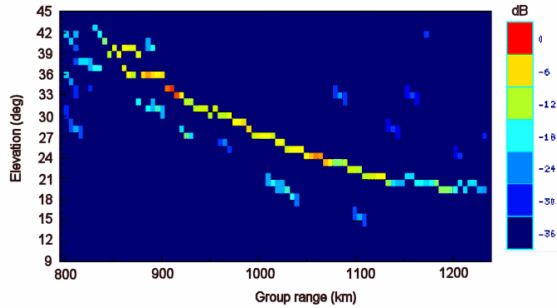


Fig. 7. Backscatter ionogram by elevation scanning

The skip distance (near 850 km) corresponds to the focalisation zone associated to the layer (F region in this case). The coordinates of the focalization (minimum of group range, focalization angle) are extracted from the ionogram and fitted to a Multi Quasi Parabolic (MQP) model.

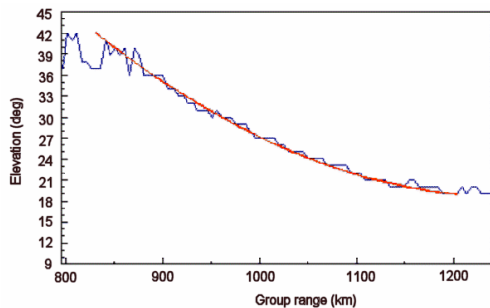


Fig. 8. Backscatter ionogram by elevation scanning fitted by a MQP modelling

The ionospheric parameters at the mid-point are determined by an inversion process (as presented on the figure below). It consists to obtain the MQP profile which gives the maximum probability to represent the medium in the refraction area.

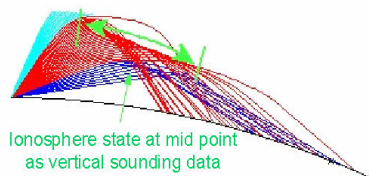


Fig. 9. Ray tracing: inversion of backscatter ionogram by scanning in elevation

By this technique, NOSTRADAMUS radar is fully autonomous to manage the ionosphere and don't need other external sounding items like vertical sounders or beacons.

## 3) Spectral surveillance

A clear channel research runs permanently in bands of operating frequencies for the radar to determine the optimum frequencies by evaluating the occupancy of the channels and the level of noise.

This measurement is realized with a biconical antenna separated from the NOSTRADAMUS array. This antenna is connected to an autonomous receiver coupled to a computer with an analogic numerical converter. A statistic based on the level of noise, is established for each channels which are classified as free or occupied.

## 4) Frequency management

The choice of the operating frequency and the performances of the radar in terms of detection and localization, are limited by the spatio-temporal variabilities of the ionosphere and by the availability of the channels of propagation.

The operating frequency is managed from the data of the different means of sounding, to determine the operating parameters which optimize the budget power for the coverage of interest.

NOSTRADAMUS FMS is principally based on the two backscatter sounding techniques: one by frequency sweeping with elevation information (**BSS**) and the other by elevation scanning at one frequency (**ELS**). The inversion of the backscatter ionograms could be done by combining these two sounding modes.

## 5) Global mapping of the ionosphere with combination of BSS and ELS soundings

BSS soundings are carried out each 10 minutes. These soundings take 40 seconds to sweep the whole band 6 to 28 MHz by step of 1 MHz. The ionogram represents the group range versus the frequency with the elevation in third dimension (cf. figure below).

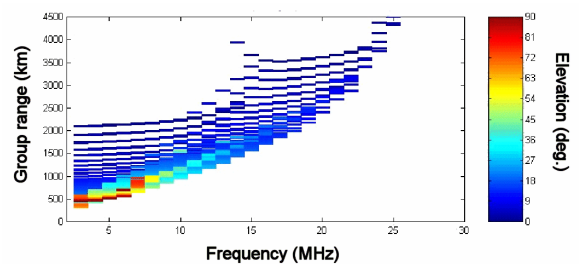


Fig. 7. Backscatter ionogram (BSS – Frequency sweeping)

This kind of ionogram is the succession of many ELS ionograms respectively obtained for each frequency and which represent the group range versus the elevation (cf. the following figure).

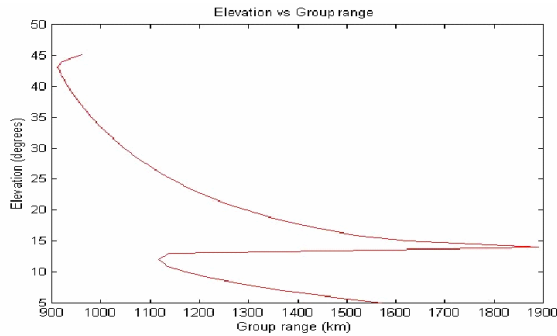


Fig. 10. ELS ionogram (Group range vs elevation)

As BSS soundings are performed in many directions in azimuth, a map of the ionosphere is also established every 10 minutes by inverting respectively all the ELS ionograms. This result becomes the input data for 2D and 3D ray tracing algorithm for the propagation prediction program and coordinates registration.

#### 6) Real-time re-actualization of the map of the ionosphere

While the system is operating in radar mode, the clutter signal is used for ELS sounding during each integration time. The inversion of the ELS ionogram gives the ionospheric parameters at mid-point of the link for this radar operating frequency in the corresponding azimuth as if a vertical sounder would be at this point.

So at each integration time, new parameters are available for a particular point of the ionosphere. As the radar sweeps in frequency and azimuth, the map of the ionosphere could be re-actualized continuously.

#### 7) Frequency management system

With the different outputs of soundings, a mapping of the ionosphere is established and re-actualized as it could have been done with data from distant vertical sounders. This map represents input data for short term predictions program and ray tracing algorithms. With these items, the FMS provides in real-time:

- the best operating frequencies for the missions of the radar in terms of coverage and type of targets to be detected,
- the coordinate registration to position targets in real coordinates for the operating frequency.

## IV. DISCUSSION

It has been described in this paper, the original concept of NOSTRADAMUS radar and the new sounding techniques using elevation information.

The monostatic and surface array as a 3 arms star, allows 360° coverage and the control of beam in elevation. This limits the problems of propagation: only one point of refraction to consider and a better control of the propagation channel.

A specific frequency management system could be implemented in the radar. The measurement of elevation angle allows inversion of backscatter soundings which gives

in real-time the ionospheric parameters at the mid-point. With these new techniques, the system is fully autonomous in all azimuths; and it doesn't need the use of distant sounders to manage the ionosphere. It provides coordinate registration to the tracking and predictions of operating frequencies in function of radar missions.

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